PREDICTING LOW VELOCITY IMPACT DAMAGE – A MIXED MODE DEGRADATION MODEL

F. Ehrich[1]*, L. Iannucci[1], J. Ankersen[1], M. Fouinneteau[2]
[1] Department of Aeronautics, Imperial College of Science and Technology, London, UK,
[2] EDSAZB - Structural Vulnerability - Numerical Simulation Development, AIRBUS, France
* Corresponding author (f.ehrich09@imperial.ac.uk)

Keywords: *Composite, Impact, Damage, Degradation, Mixed mode*

1 Introduction

Due to their high specific mechanical properties, fiber reinforced composites are widely used in aerospace applications. However, impact loads can cause substantial damage in these materials reducing strength and stiffness significantly.
During impact loading, various loading conditions can occur resulting in diverse damage patterns. For the prediction of damage initiation, many failure criteria have been published which presume an interaction of different stresses in the formation of damage [1]. However, the most common damage models for predicting impact damage [2, 3, 4] consider only directly associated stresses for damage propagation. None of these models accounts for damage interaction in the post failure regime.
This paper presents a novel energy based damage model accounting for damage interaction. The predictions are compared to impact experiments carried out on carbon-epoxy composite plates.

2 Damage Model

The presented damage model is a two dimensional plane stress model for shell elements [5]. It is based on a combination of damage mechanics and fracture mechanics with five damage variables per ply accounting for the following damage modes:

- Tensile damage in fiber direction
- Compression damage in fiber direction
- Tensile damage in transverse direction
- Compression damage in transverse direction
- Shear damage

After appropriate initiation criteria have predicted the onset of damage, corresponding material properties are progressively degraded. For mixed mode loading conditions, interaction of failure modes is accounted for in both damage initiation and damage propagation.

2.1 Material Degradation

Damage propagation is modeled by progressive degrading of material properties following a damage mechanics approach. By means of five different damage variables d_i, initial material stiffnesses E_i^0 are degraded to represent the stiffness E_i of the damaged lamina:

$$E_i = (1 - d_i)E_i^0 \tag{1}$$

The damage variables vary between d_i=0 for the undamaged material and d_i=1 for the fully failed material.

2.3 Damage Initiation

Damage initiation for fiber failure is predicted by means of a maximum stress criterion for direct stresses. For tensile and compressive damage, the failure criteria are:

$$F_{1t} = \frac{\sigma_{11}}{X^T} \leq 1 \tag{2}$$

$$F_{1c} = \frac{|\sigma_{11}|}{X^C} \leq 1 \tag{3}$$

Where X^T and X^C are the strength in tension and compression, respectively.
For matrix failure under transverse tension, damage initiation is calculated using a stress-based interaction criterion for transverse direct stresses and shear stresses:

$$F_{2t} = \left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\tau_{12}}{S^C}\right)^2 \leq 1 \tag{4}$$

Matrix failure under transverse compression is predicted by means of a Mohr-Coulomb criterion based on the effective shear stresses τ_{eff}^T and τ_{eff}^L

on the fracture plane with the angle α as shown in Fig. 1[6]:

$$F_{2c}(\alpha) = \left(\frac{\tau_{eff}^{T}}{S^{T}}\right)^2 + \left(\frac{\tau_{eff}^{L}}{S^{L}}\right)^2 \leq 1 \qquad (5)$$

Thereby, S^T and S^L are the corresponding shear strengths in the fracture plane.

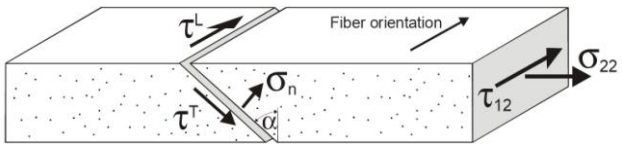

Fig.1. Fracture plane with fracture angle α [6].

2.4 Damage propagation

After damage initiation is predicted, the damage is propagated until final failure. Damage propagation is expressed in terms of strains within the lamina. Between damage initiation and final failure a linear unloading is assumed. The material degradation is outlined in Fig. 1. To fully describe the damaging process, two strain values are necessary: the strain at damage initiation ε_0 and the strain at complete failure ε_{max}:

$$d_i = \frac{\varepsilon_{max}}{\varepsilon_{max} - \varepsilon_0}\left[1 - \frac{\varepsilon_0}{\varepsilon_i}\right] \qquad (6)$$

The damage initiation strain ε_0 results from the initiation criteria discussed above. For the calculation of ε_{max} fracture mechanics are introduced: it is assumed that the energy dissipated during the material degradation equals the material's fracture toughness G_c for the same failure mode.
To be able to compare the volumetric strain energy and the fracture energy the characteristic length l^* is introduced:

$$\frac{1}{2}\sigma_c \varepsilon_{max} = \frac{G_C}{l^*} \qquad (7)$$

The characteristic length is a mesh parameter and its introduction ensures solutions independent of mesh size.

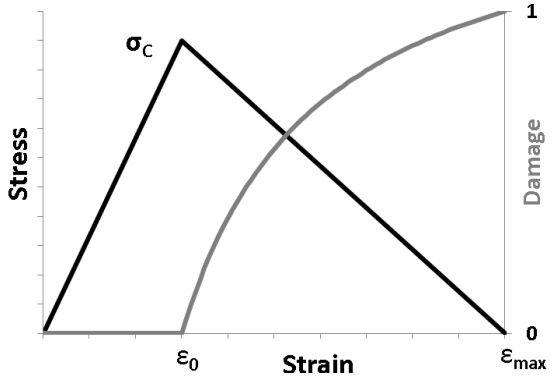

Fig.2. Stress-strain behavior of damaged lamina.

2.5 Mixed Mode Damage

For the initiation of matrix damage the interaction between transverse direct stresses and shear stresses is experimentally proven [1] and has been implemented in this model for predicting damage initiation. For the behavior after damage initiation, such an interaction is very likely to persist. Thus, in the damage model presented here, an interaction between transverse and shear deformation in the post-failure regime is assumed. This is in contrast to many existing material damage models [2, 3, 4] which model damage propagation separately for each failure mode. In this novel interactive damage model presented here, a quadratic interaction between transverse direct strains and shear strains is implemented. Final failure is computed by means of a power law based on the maximum strains for pure loading conditions:

$$\left(\frac{\varepsilon}{\varepsilon_{max}}\right)^2 + \left(\frac{\gamma}{\gamma_{max}}\right)^2 = 1 \qquad (8)$$

The maximum strains for pure modes ε_{max} and γ_{max} are computed according to equation (7).
The resulting final failure envelope (shown in Fig. 3.) is independent of the damage initiation criterion.
Damage is assumed to propagate along a line through the origin and the current strain state $(\varepsilon_i, \gamma_i)$. After damage initiation, transverse stresses and shear stresses are linearly reduced until final failure occurs simultaneously for both failure modes. Damage propagation is described by means of the strain values at initiation $(\varepsilon_d, \gamma_d)$, the strains at final failure $(\varepsilon_f, \gamma_f)$ as well as the current strains $(\varepsilon_i, \gamma_i)$ according to:

$$d_2 = \frac{\varepsilon_f}{\varepsilon_f - \varepsilon_d}\left[1 - \frac{\varepsilon_d}{\varepsilon_i}\right] \quad (9)$$

$$d_3 = \frac{\gamma_f}{\gamma_f - \gamma_d}\left[1 - \frac{\gamma_d}{\gamma_i}\right] \quad (10)$$

The damage propagation path is re-calculated at every time step to account for load re-distribution and changes in damage mode ratio.

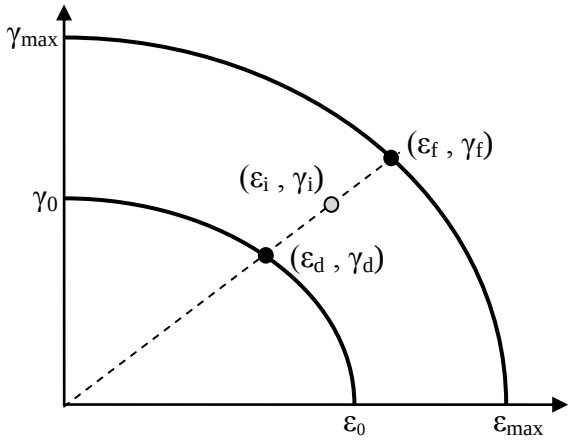

Fig.3 Current strains (ε_i , γ_i) with corresponding initiation strains (ε_d , γ_d) and failure strains (ε_f , γ_f).

2.6 Minimum Element Size

For the presented damage model a minimum element size exists depending on the material parameters.

As it is apparent from Fig. 2, the strain at final failure ε_{max} cannot be smaller than the strain at damage initiation ε_0. Thus, considering (7) a minimum characteristic length l^* is defined by:

$$l^* < 2\frac{G_C E}{\sigma_c{}^2} \quad (11)$$

3 Model Implementation

The damage model is implemented as a VUMAT user material in the commercial finite element code ABAQUS/Explicit. It can be used in conjunction with both, conventional shell elements and continuous shell elements. After complete damage of the matrix or the fibers, elements are deleted from the analysis.

4 Impact Simulation

Impact simulations are carried out on plates discretized with a stacked shell approach consisting of 8-node continuum shell element layers representing two sub-laminates connected with a layer of cohesive elements of 0.02 mm thickness in the centre of the plate. The cohesive layer is necessary to account for interlaminar damage which cannot be predicted by the two dimensional in-plane damage model presented here.

For model validation, the simulation results for contact force, displacement and delamination damage are compared to low velocity impact experiments carried out on T800s/M21 carbon/epoxy plates. The specimens were impacted with a spherical steel impactor of 2.6kg mass with 30J impact energy.

4.1 Impact Response

In Fig.4 the force-time response of a 30J impact experiment (black) is compared to a simulation (grey) of the same experiment.

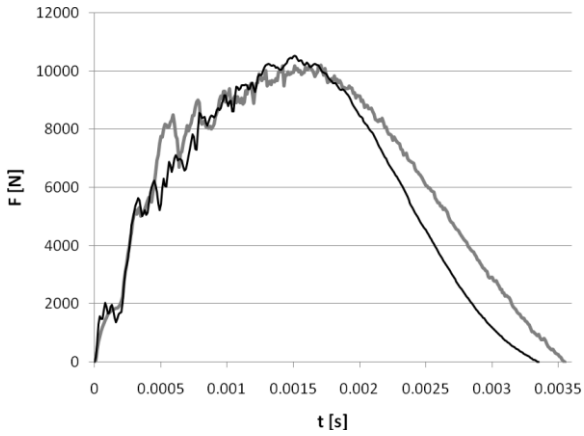

Fig.4 Force-time comparison impact experiment (black) and simulation (grey)

The general impact response of the simulation follows the experimental data quite well. During the elastic response in the beginning of the impact, the correlation of simulation and experiment is very close. While damage load is predicted quite accurately by the model, there is a certain offset of the force-time curve during the early phase of damage propagation. The simulation's peak load correlates quite well with the experiment while the contact duration is slightly over-predicted.

4.2 Impact Damage

The impact damage in the experiments was quantified by the delamination area detected by ultrasonic scanning of the impacted plates. The resulting image shows a maximum envelope of all damages occurring in different interfaces. A post-impact C-scan image of a plate impacted with 30J impact energy is shown in Fig. 5.

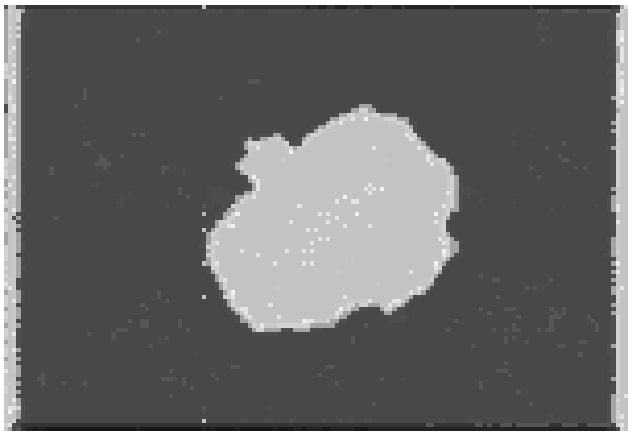

Fig.5 C-Scan image of impacted plate

In the simulation, delamination damage prediction is based on failure of cohesive elements located in the centre of the plate between the two sub-laminates. Damage is defined by a quadratic interaction of fracture energies.

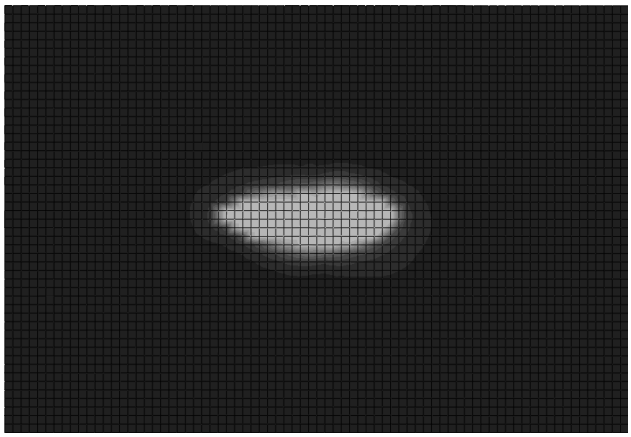

Fig.6 Delamination prediction from Simulation

Comparing the delamination prediction with the C-scan image shows a clear under-prediction of delamination damage in the simulation. This can be caused by the simple modeling approach with only one cohesive layer or by neglecting any interaction of intralaminar damage and delamination.

5 Conclusion

A novel progressive damage model for impact damage prediction is presented. The interaction of loading in transverse direction and shear direction are included for predicting damage onset and final failure. The presented model replaces previous non-interactive models with a more physically meaningful modeling approach.

The model's impact response prediction is very close to experimental data. However, delamination damage is clearly under-predicted which needs further investigation.

Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Program FP7/2007-2013 under grant agreement n°213371 (www.maaximus.eu).

References

[1] A. Orifci, I. Herszberg and R. Thomson. "Review of methodologies for composite material modeling incorporating failure". *Composite Structures*, Vol. 86, pp 194-210, 2008.

[2] P. Ladeveze and E. LeDantec. "Damage modelling of the elementary ply for laminated composites". *Composites Science and Technology*, Vol. 43, No. 3, pp 257-267, 1992.

[3] P. Maimí, P. Camanho, J. Mayugo and C. Dávila. "A continuum damage model for composite laminates: Part I – constitutive model". *Mechanics of Materials*, Vol. 39, No. 10, pp 897-908, 2007.

[4] L. Iannucci and J. Ankersen. "An energy based damage model for thin laminated composites". *Composites Science and Technology*, Vol. 66, pp 934-951, 2006.

[5] L. Iannucci, J. Ankersen and F. Ehrich. *A fracture based damage model for impact predictions*, ECCM-2010, Paris, (2010).

[6] C.G. Davila, P.P. Camanho and C.A. Rose. "Failure Criteria for FRP Laminates". *Journal of Composite Materials*, Vol 39, No. 4, pp 323-345, 2005